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ARTICLE

A Simple and Effective Process to Join Coated Superconductors at a Low Resistance

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Abstract: With recent advances on the performance of the YBCO coated conductor (CC) tape, its attractive perspectives for application have opened up for us. Joining process of CC tapes is inevitable for development of coated superconductor based apparatuses where single tape is not long enough or needs to be looped. Generally the joint was completed at a certain temperature and under a constant pressure that were investigated in prior literatures. Because the CC tape is very thin, and easy to damage because of deformation in some region of the tape, the surface of the joint making table should be flat and smooth enough, which have not received serious attention yet. Meanwhile, the smoothness of the pressing table is crucial to obtain the joint with low resistance. In this paper, a simple and effective joint of coated superconductor tapes making process depending on a soldering table with high smoothness less than 5 μm/100 mm was investigated. In the process, the non-superconducting lapped joint method with face-to-face configuration was employed, and the solder layer thickness and the joint lapped length varied. The current-voltage characteristic of the jointed tapes was measured in liquid nitrogen bath by a standard four-probe technique. The joint with sufficiently low resistance of 6.3 nΩ was easily achieved with a lapped length of 14 cm, which is ascribed to the use of a soldering table with high smoothness. In addition, the joints microstructure was observed by the metallographic microscope and scanning electron microscopy (SEM) to reveal the distribution of the solder between the joined CC tapes.

Key words: superconducting tapes; electrical joint; critical current; resistance

A substantial effort has been devoted in recent years to develop the coated superconductor (CC) based applications for the advantages of its very high critical current under high magnetic field and relatively higher operating temperature than the low temperature superconductors, meaning the possibility of reducing cooling cost. The commercial CC tape with sufficient length is currently still unavailable due to the limited production capacity of the manufactures. The promising apparatuses of using CC tapes, such as electric machines and magnets[1-5], have consequently the crucial issue that the tapes have to be joined, for the purpose of building large coils and implementing of the persistent current mode. Therefore, the development of the electrical joint for CC tapes is indispensable to its applications, and a simple and practical joint made procedure is significant.

Previous studies mainly presented three types of electrical joints, including superconducting joint, soldering joint and diffusion joint[6-17]. For engineering applications, the soldering and diffusion techniques are considered to have better operability. As to different purposes, the CC tapes can be joined in three configurations, i.e., lapped, bridged and butted, as shown in Fig.1.

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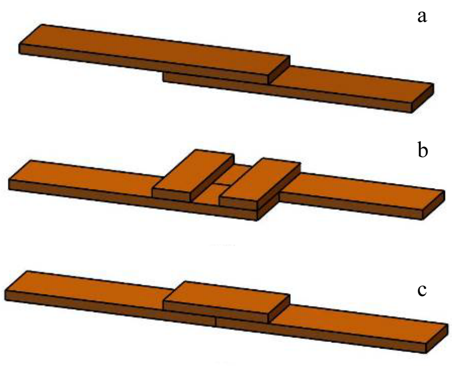

Fig.1 Schematic view of the electrical joint configuration for coated superconductor: (a) lapped joint, (b) bridged joint, and (c) butted joint

In order to easily get the joint with excellent electrical properties there are some key factors to consider when making the joint. Since the high temperature can cause degradation in superconductivity of tape, it is recommended that soldering temperature should be kept as low as possible. Using low melting point solder will help to avoid such damage of the CC tape. Different soldering materials, such as PbSn, InBi, SnAgCu, SnAg and InSn, were employed to investigate their effect on the contact resistance [7-9]. In addition, appropriate pressure should be applied to the joint for a desired performance on the resistance, critical current and n-value. Kim et al.[10] investigated the relation between the joint properties and the applied pressure. Another factor which should be paid more attention to is the smoothness of the joint making table. As the CC tape is very thin, its superconductivity is easy to be degenerated because of the deformation of the tape when the pressure was applied in the condition of a soldering table with low smoothness. Moreover, the solder between the tapes cannot spread well to fulfill the gap. However, although a great deal of research has been completed on the procedure and factors and how it affects the electrical properties of the joint, little attention has been paid to the factor of the table surface's smoothness.

In this paper, depending on a soldering table with high smoothness, less than 5 μm/100 mm, a simple and effective lapped joint soldering procedure for superconducting coil was developed. Several joints with various lapped lengths and solder thicknesses were fabricated. The current-voltage characteristic curves of the produced joint samples were measured via a four-probe method in a liquid nitrogen bath.

The electrical properties of the joint, including contact resistance, critical current and n-index value, were derived from the V-I curve. The critical current and n-index value of those joints were compared with the pristine tapes. Then the optical and scanning electron microscopy were used to evaluate the microstructure of the joints.

1 Experiment

Electrical joint with low resistance is significant for the development of persistent current mode system using the YBCO CC tapes. The current retaining in the coil can be evaluated by Eq. (1) below. Table 1 shows a calculation result of residual current ratio for a 1-H coil, while its resistance varies. It is apparent that the current decays too fast to achieve persistent current mode with a high resistance.

$$I_t = I_0 e^{-(Rt/L)} \quad \text{and} \quad \mathrm{RCR} = \frac{I_t}{I_0} = e^{-(Rt/L)} \tag{1}$$

where I_t is the residual current, I_0 is the initial current, R and L are the resistance and inductance of the coil respectively, and t is the time. RCR is defined as the residual current ratio.

1.1 Investigated samples

The commercially available YBCO CC tape SCS4050, produced by Super Power, has been used to prepare the lapped joints. The tape is a multilayer composite which is stacked with copper stabilizer, silver layer, YBCO layer, buffer and substrate, and its layout is drawn in Fig.2. The electrical joints with different lapped lengths (5, 8 and 11 cm) and various solder thickness (20, 10 μm and less than 10 μm) were made.

1.2 Lapped-joint made procedure

Table 1 Residual current ratio (RCR) in a 1-H coil

Resistance/nΩ	RCR/%		
	24 h	30 d	180 d
500	95.77	27.36	0.04
50	99.56	87.84	45.95
5	99.96	98.71	92.52

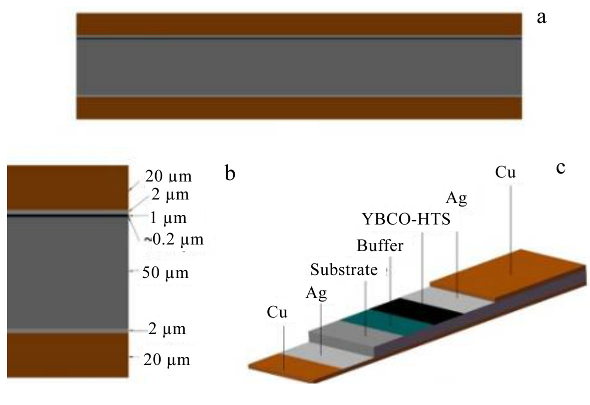

Fig.2 Schematic view of the studied YBCO CC tape (Super Power SCS4050)

In the present study, we developed a new type of high smooth soldering device that has advantages of simple construction, easy operation and good repeatability. The soldering device contains an electronic control heater and a pressing table, being used to heat and press the sample, respectively, as shown in Fig.3. Its key character, being different from the existing counterparts, is that the surface of upper block and lower block of the pressing table has high smoothness of less than 5 μm/100 mm, which is considered to be a crucial point in our proposed joint making process. Also, the electronic heater supplied a stable temperature in joint making step by a feedback control system. The constant pressure applied on the joint was implemented and estimated by the screw of fixed block and torque wrench, respectively.

The processing technique to join YBCO CC tapes comprised four steps, including pressing table preheating, YBCO CC tapes cleaning, joint making and table cooling down. The upper block was put down when preheating so that it can be heated up along with the lower block simultaneously. To minimize the influence of the surface impurities on the contact resistance, the tape was polished slightly and cleaned with souring pad and ethyl alcohol. When the lower block was heated up to 235 °C, the upper block was lifted and the two tapes were placed on the lower block surface with the YBCO layer kept up.

Then, a small amount of solder flux for proper wetting and just enough Sn-Bi solder was spread uniformly on the tape with a determined length. After that, the tapes were overlapped carefully with a face-to-face configuration on the lower block surface. Subsequently, the upper block was dropped and pressed on the tape by the screw with a compressive pressure, which was estimated with controlling torque of 50 Nm. The last step was to wait the table cooling down to room temperature with a constant pressure applied on the joint. The solder thickness was controlled by the shims with different thicknesses. All samples, varying in lapped length and joint thickness, had been subjected to the same heat treatment and constant pressure during the joining process.

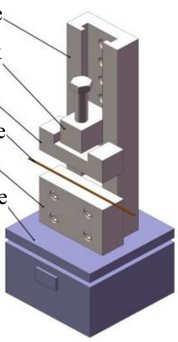

Fig.3 Three-dimensional model of the lapped joints soldering device having a high smooth interface of the upper block and lower block

1.3 Electrical properties measurement

The joint electrical properties test was carried out at 77 K via the four-probe method. For purposes of comparison, the characteristic curve of each pristine tape was obtained prior to cutting and jointing. The governing equation of the characteristic curve is as follows:

$$V = R_j I + V_c \left(I / I_c \right)^n \qquad (2)$$

where R_j is the contact resistance, V_c is criterion voltage based on the criterion of E_c = 1 μV/cm, I_c is the critical current, and n is the index number depending on the material [11]. The value I_c is equivalent to the current value at $V = V_c$. The joint resistance equals the slope of the characteristic curve and the n index value is calculated by Eq. (2).

In the experiment, an Agilent 6680A programmable DC power supply and an Agilent 34401A digital nano-voltmeter were employed as the current source and voltage monitor, respectively. A test system based on LabVIEW was introduced for current output controlling and voltage data acquisition. In order to validate the accuracy of the result, the measurement was conducted repeatedly for three times on each sample.

1.4 Microstructure scanning

The interfacial microstructure characteristics of the joint were further investigated by the optical and scanning electron microscopy (SEM). The joint sample was cut at first and then mounted in a castable mounting resin block. This mounting resin is a typical cold mounting resin which cures in less than 1 h and the highest temperature is lower than 80 °C during curing, so there will be no influence on the joint microstructure. In addition, the surface of the resin block must be rubbed slightly with different specification from 600# to 2000# grit SiC paper under running water and polished with diamond grinding paste before observation.

2 Results and Discussion

2.1 Electrical properties of the samples

As mentioned above that the electrical properties, including resistance, critical current and n-index value, of the joint are the primary concern in making joint. All the YBCO CC samples were electrically characterized at 77 K, and these three parameters can be derived from the *V-I* characteristic curve of the samples. In this section, we compared the influences of the overlapped length and the solder thickness on the resistance (R_j), as well as on the achievable critical current (I_c) and n-index value with the electrical joint fabricated by the proposed process.

The resistance and resistivity (R_{js}) data were plotted in Fig.4. R_j and R_{js} characteristics were observed to vary with the length and thickness of the joint. The resistance curves illustrate a reasonable relationship between the R_j and the length and thickness, which corresponds to the material

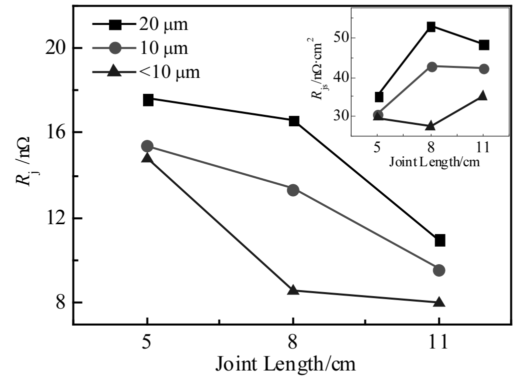

Fig.4 Chart of resistance and resistivity of joint samples for different joint length (solder thickness) (revealing that the resistance decreases with increasing the joint length or reducing the solder thickness. However, the joint sample with longer length has a larger resistivity)

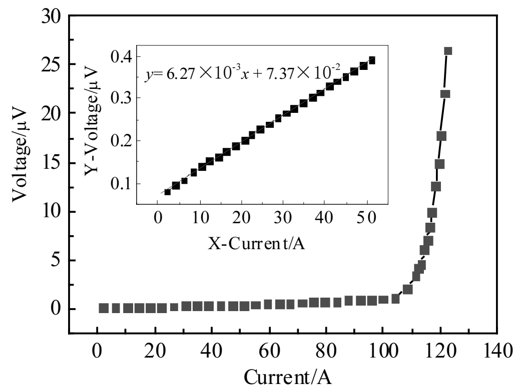

Fig.5 *V-I* characteristic curve for the sample with length of 14 cm and thickness less than 10 μm

resistance-resistivity relation Eq.(3). It is easily understood from the *R*-*ρ* relation that, once the joining process is optimized and determined, two measures are considered useful to reduce the joint resistance, viz., making the joint area wider and the solder thickness thinner. The joint area can be controlled simply through varying the lapped length. Given the solder thickness is demanded to be controlled at the micron scale, not only the applying compressive pressure level which were investigated by prior literatures, but also the smoothness of the pressing table surfaces which is proposed in this paper should be considered. In addition, the pressure applied on the tapes can be uniform, which is crucial to obtain the joint with low resistance, only if the surface of pressing table is flat and smooth enough.

$$R=\rho\left(L_s/S\right) \quad \text{and} \quad S=L_o\omega_o \tag{3}$$

where ρ and L_s are the normalized resistivity and the thickness of the solder between the YBCO layers, respectively, L_o is the overlapped length and ω_0 is the tape width.

Fig.4 shows that the resistance decreases from 17.6 nΩ (5, 20 μm) to 8 nΩ (11 cm, less than 10 μm). In further experiments, the best case of 6.3 nΩ (14 cm, less than 10 μm) was achieved, as shown in Fig.5. Conversely, the joint with larger lapped length has a higher resistivity. It could be inferred that, the solder is distributed more evenly in the shorter joint, which beneficially results in a lower R_{js}.

In the literatures, resistance of the joints had been measured and discussed. An overview of the results of the recorded resistance in these studies is given in Table 2, from which it is known that most of the joints have the resistance higher than 10 nΩ, especially in the literatures

Table 2 Resistance comparison of SCS4050 joints

Year	Group	R_j /nΩ	R_{js}/nΩ·cm^2
2009	Korea University [12]	23	-
2010	Andong National University [13]	4.3	3.44
2011	Yonsei University [14]	7	33.6
2012	KIT [15]	54	194
2012	CEA [7]	-	35
2012	Yonsei University [10]	11	30.8
2013	UNESP [16]	16.2	41.8
2014	Sophia University [17]	58	-
2015	MIT [1]	9	-

whose subject was on the practical application with YBCO CC tapes. It means that the joint making process proposed in this paper is reliable and useful.

In this paper, the critical current ratio value was defined as the ratio of critical current of the resistive-jointed tape to the pristine tape, i.e., CCR = I_c/I_{c0}. The characteristic curves of both pristine tapes and resistive-jointed tapes are given in Fig.6. The samples with the same overlapped length were fabricated repeatedly and tested with the same joining process and measurement condition. From Fig.6, it can be observed that the samples were divided into two groups. The critical current was slightly higher than that of the pristine tape in one group, joints with the length of 8 cm and 11 cm, while the critical current degradation occurred in the other group, 5 cm-long joints. It means that the CCR value is more than one and less than one, respectively.

The positive alteration of the critical current in the first case may be caused by the extension of the pathways of the current in the joint area. It is evident that the high smoothness of the pressing table is helpful for maintaining the critical current. In another case, the amplitude of critical current degradation is less than 20 percent of pristine

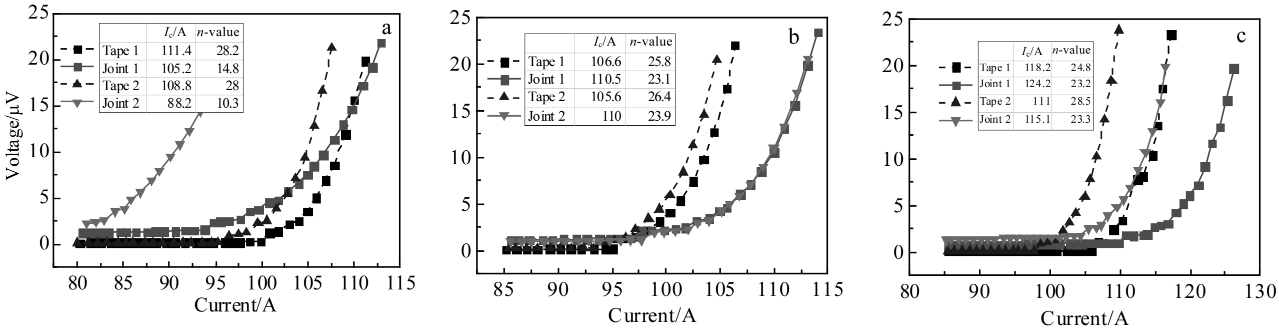

Fig.6 Characteristic curves of the pristine tape and corresponding joint, representing by dash and solid, respectively: (a) 5 cm-long joints, (b) 8 cm-long joints, and (c) 11 cm-long joints

critical current. The pressure applied on the joint could bring about the decay of I_c in the second case, as the compressive force applied on the three kinds of joint with different lengths is identical but the lapped areas are different, meaning the pressure are different. It is therefore speculated that the overpressure is one possible cause of the degradation of critical current on 5 cm-long samples.

2.2 Microstructure analysis

Microstructure of the cross section of the joints was evaluated by metallographic microscope and SEM. As can be seen in Fig.7, the solder spreads fully in the gap between the two tapes. This finding indicates that there is a close contact on both boundaries of the solder layer, which is the pre-requisite for achieving low resistance. However, this figure also displays that the thickness of solder increases from the center to the end in samples because of the inherent wrapping characteristic along with the traverse direction of the tape, as shown in Fig.8. Therefore, more

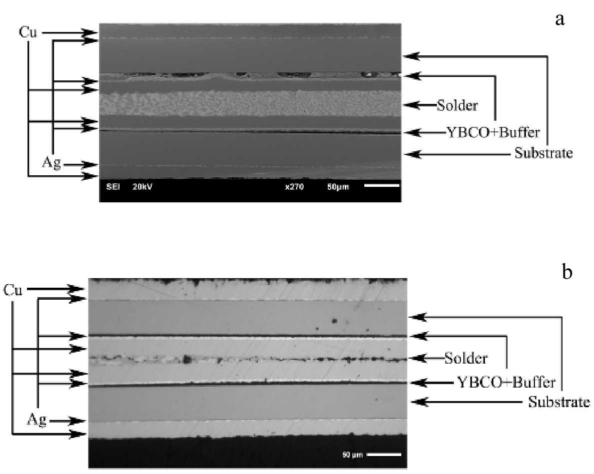

Fig.7 Micrographs of the transverse cross-section of jointed sample by SEM (a) and metallographic microscope (b)

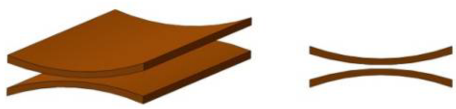

Fig.8 Schematic view of the inherent wrapping characteristic along with the traverse direction of the tapes

studies on the improvement of the uniformity of the solder layer by control the pressure need to be carried out. Meanwhile, whether the change of the wrapping will cause degradation of the superconductivity need to be investigated, which have not been mentioned in previous literatures.

In addition, it is obvious that the YBCO layer delaminated in some area, which could be caused by the long heat process and/or overpressure. It can be considered that the specimen showing low CCR value is due to the delaminating. From the analysis of the micrographs, the condition of the solder between the tapes was obtained, meanwhile some defects existing in the joints were found, which defines the direction for the further improvement of the joint process.

3 Conclusions

1) The high smoothness of the soldering table surface is a key point to join the coated superconductors at a low resistance. An easy and effective joint process depending on a new type of high smooth soldering device for YBCO CC tapes has been developed.

2) Increasing the length of the lapped region and decreasing the thickness of the solder contribute to reduce the resistance of the joints.

3) The prevailing Superpower 2G HTS production 4 mm wide wire SCS4050 has been used as a representative. Several joints varying in lapped length and joint thickness

were fabricated and measured. The critical current, *n*-value, and the contact resistance of the joints were evaluated and the results show a good electrical performance. The lowest resistance of the joint is 6.3 nΩ.

4) It is certain that more uniform solder layer diffusion and low YBCO layer deformation would improve the resistance and CCR value, respectively. Further optimization of the joint process to improve its capability is in progress by controlling the heating time and temperature plus the pressure more precisely.

References

1 Lecrevisse T, Bascunan J, Hahn S *et al. IEEE Trans Appl Supercond*[J], 2015, 25(3): 6 602 505

2 Bromberg S Ito L, Takayasu M, Minervini J *et al. IEEE Trans Plasma Sci*[J], 2012, 40(5): 1446

3 Li J, Yen F, Zheng S *et al. Low Temp Phys*[J], 2014, 174(1): 87

4 Xie S F, Wang Y, Wang D Y *et al. J Low Temp Phys*[J], 2013, 170(5): 366

5 Watanabe K, Awaji S, Koyama K *et al. J Low Temp Phys*[J], 2010, 159(1): 370

6 Brittles G D, Mousavi T, Grovenor C R M *et al. Supercond Sci Technol*[J], 2015, 28(9): 093 001

7 Lécrevisse T, Gheller J M, Louchart O *et al. Physics Procedia* [J], 2012, 36: 681

8 Chang K S, Park D K, Yang S E *et al. IEEE Trans Appl Supercond*[J], 2009, 19(3): 2419

9 Sugano M, Nakamura T, Shikimachi K *et al. IEEE Trans Appl Supercond*[J], 2007, 17(2): 3067

10 Kim H J, Hwang Y J, Choi S *et al. IEEE Trans Appl Supercond*[J], 2012, 22(3): 4 703 505

11 Sohn M H, Kim S W, Baik S K *et al. IEEE Trans Appl Supercond*[J], 2003, 13(2): 1764

12 Kim H S, Kwon N Y, Chang K S *et al. IEEE Trans Appl Supercond*[J], 2009, 19(3): 2835

13 Shin H S, Dedicatoria M J, Oh S S. *IEEE Trans Appl Supercond* [J], 2010, 20 (3): 1447

14 Chang K S, Jo H C, Kim Y *et al. IEEE Trans Appl Supercond* [J], 2011, 21(3): 3005

15 Nast R, Ringsdorf B, Jung A *et al. Physics Procedia*[J], 2012, 36: 1614

16 Baldan C A, Oliveira U R, Bernardes A A *et al. J Supercond Nov Magn*[J], 2013, 26(5): 2089

17 Isozaki K, Iwasaki S, Anazawa T *et al. IEEE Trans Appl Supercond*[J], 2014, 24(3): 8 400 304

一种简便有效的涂层超导带材低电阻焊接工艺

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摘 要：随着近年来YBCO涂层超导带材性能的提升，其相关应用已逐渐成为研究热点。由于单根带材长度通常不能满足实际应用需要或需要形成闭合线圈，涂层超导带材的连接是各项应用中必不可少的一个关键步骤。国内外对带材接头工艺中控制因素的研究主要集中在焊接温度、焊料、施加压力等方面。由于涂层带材很薄，极易因为局部的微小形变而损坏退化，因此焊接平台表面应该足够平整光滑，焊接平台具有高平整度表面也是获得极低电阻接头的关键因素之一，而目前这一点还未引起足够重视。因此研究了一种简便有效的基于高平整度（小于5 μm/100 mm）焊接平台的涂层超导带材焊接工艺。采用该工艺及带材正面相对的搭接方式，进行了不同厚度和搭接长度的带材接头焊接。之后，采用四引线法在液氮环境中对接头进行了电性能测试，当搭接长度为14 cm时接头电阻低至6.3 nΩ。此外，通过金相光学显微镜和扫描电子显微镜对接头微观结构进行了观察分析，获得了接头处焊料分布状态。

关键词：超导带材；接头；临界电流；电阻

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